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Effect of Explosion Bulge Test Parameters on the Measurement of Deformation Resistance for Steel

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ABSTRACT

This paper investigates the effects of varying some of the explosion bulge test conditions on assessment of the plate deformation resistance (bulge depth and plate thinning), focusing on four parameters: (a) use of cardboard wrapping to provide thermal insulation for the test plate prior to blasting (b) changing the means of supporting the charge above the plate from a cardboard box enclosure to a suspended stocking, (c) effect of testing temperature, and (d) the effect of crack starter weld beads on plate deformation. Of the four parameters, it was found that the use of a cardboard box enclosure provides measurably different outcomes compared to a charge suspended from the ceiling by a stocking.

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Executive Summary

The Explosion Bulge Test has been used for over 60 years as a standard test for the assessment of steel toughness and deformation resistance under blast loading conditions [1-3]. However, details of the test conditions vary considerably from one country to the other. For example, the Australian test is almost identical to that used in the USA, while in the UK and Germany the test is conducted under water and hence test conditions are substantially different.

This paper investigates the effects of varying some of the test conditions and assessing the ultimate test outcomes, focusing on four parameters: (a) use of cardboard wrapping to provide thermal insulation for the test plate prior to blasting; (b) changing the means of supporting the charge above the plate from a cardboard box enclosure to a charge held in a stocking and suspended from the ceiling; (c) effect of temperature; and (d) the effect of crack starter beads on plate deformation.

Of the four parameters evaluated in this study, it was found that replacement of the cardboard box enclosure with a charge suspended over the test plate may produce differing bulge depth results. The other parameters have no measurable influence. It is concluded that use of the cardboard box enclosure for supporting a charge of the Explosive Bulge Test should not be varied.

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Brian Dixon is a metallurgy scientist in the Maritime Platforms Division of Defence Science and Technology Organisation. He has been employed at DSTO since 1978, undertaking experimental development and fundamental studies into weld metal solidification cracking in steels and stainless steels. He has also undertaken extensive work on improving the weld zone toughness of high strength steels. During 1989 and 1990 Brian worked at Kockums Laboratory in Sweden as part of DSTO's contribution to the submarine project. Since 2001, Brian has worked in a number of developmental positions, including Director, Program Office (Maritime), STCC for M1 and M6 and S&T Adviser for JP 2048. He is currently head of the Armour Mechanics and Vehicle Survivability Group.

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Nomenclature

AMT	Ambient temperature
EBT	Explosion Bulge Test
BD	Bulge depth
CBW	Cardboard wrap as insulation to maintain required plate test temperature
CBE	Cardboard box enclosure for 320 mm distance between plate and charge
CCD	Charge cylinder diameter
CW	Crack starter
NCW	No crack starter weld bead

1. Introduction

Faced with a broad range of conventional and home-made weapons, modern armoured vehicles and associated equipment need effective armour protection. For steel armour, the mechanical properties that are most influential in protective performance are hardness, strength, ductility, and toughness (see [4-12]). A second consideration is the weight, which influences performance and manoeuvrability, operating costs and maintenance requirements of up-armoured vehicles. The armour industries have identified a number of candidate materials to protect and reduce the weight of armour vehicles [13-18]. These candidate materials require qualification, in terms of metallurgical and structural integrity analyses, as well as ballistic and blast performance before informed decisions can be made for potential utilisation of these materials into armoured vehicles.

The Explosive Bulge Test (EBT) has been used for a number of years to characterize the toughness, deformation resistance and dynamic plasticity of structural and armour materials subjected to rapid loading under the blast regime. DSTO has undertaken a number of explosive bulge tests to characterize and analyse candidate armour materials, as reported in [4]. Following [4], a number of test parameters were identified that may influence test results. These include: test temperature; use of cardboard wrapping to maintain plate temperature; use of a crack starter weld bead to evaluate deformation resistance of the steel plate; and two methods to suspend the explosive charge at a height above the flyer plate.

Some of these parameters directly influence the time and costs required when undertaking the EBT and may have implications for safety when conducting the test. The purpose of this investigation was to assess the effects of these parameters on the material performance when subjected to explosive blast loading. It is essential that the effects of these parameters be well understood and hence characterized, before considering any possible changes to the EBT procedure in order to ensure that new results are directly comparable with those results previously determined in past studies.

2. Experiments

2.1 Explosion Bulge Tests

In this investigation, the EBT was carried out at ambient (AMT) temperature and -18 °C. Deformation resistance of the plate was measured in terms of both bulge depth and thinning at the plate centre.

A series of EBTs were performed on Grade 350 mild steel plate possessing thicknesses of 3 to 10 mm using a charge weight (PE4 high explosive) of 0.46 kg. The charge shape was cylindrical, with diameters of 100 mm and 160 mm.

Before testing, each test plate was plasma-cut to dimensions of 760 mm x 760 mm to match the dimensions of the die block. Plates for EBT were prepared with a crack starter weld beads, 50 mm long and 10 mm wide, oriented along the plate rolling direction (Figure 1). These weld beads are composed of hard facing material that is inherently brittle and, under blast loading, act as a crack starter to force the initiation of brittle cracking in the weld zone and subsequently into the parent plate. Resistance to cracking is related to the toughness of the plate material.

The plate was clamped with a bolted shackle in order to avoid the blasted plates impacting the ceiling of the blast chamber. To enable clamping, holes were drilled in two opposing corners of each plate. For the plates to be tested at $-18\text{ }^{\circ}\text{C}$ (the standard test temperature for the EBT), a type 'k' thermocouple was spot-welded to the topside of the plate to ensure correct temperatures were achieved prior to testing. The plates were conditioned at approximately $-40\text{ }^{\circ}\text{C}$ and left to equilibrate overnight before testing. The thermocouple was then connected to a NI 9213 Module with 16 channels and 24 Bit thermocouple inputs from National Instruments (NI). The NI module was then connected to the NI cDAQ 9172 chassis, which was in turn connected to a notebook computer by a USB port. A schematic of the test plate is shown in Figure 1, identifying the location of the crack starter weld beads, blast chamber, thermocouple and clamp positions.

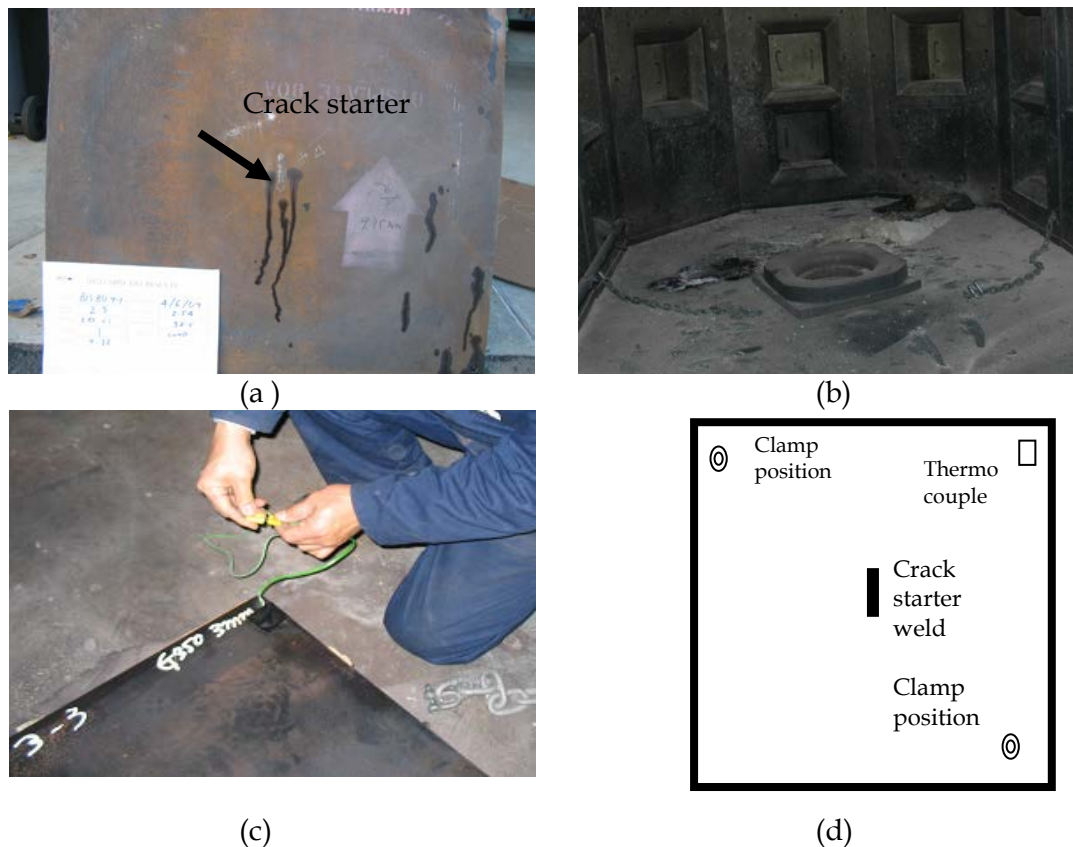


Figure 1: (a) weld bead on the centre of the plate (arrowed) (b) view of the blast chamber, (c) thermocouple position on the edge of the test plate and (d) the schematic sketch.

The plate thinning was measured as shown in Figure 2(a) at 6 points. Thickness was measured at two points on the edge of the plate (A) and four points in the centre (B) where deformation was greatest. The bulge depth was measured from the flat surface of the plate to the maximum bulge of the plate after a blast (Figure 2b). The percentage thinning was estimated by the formula $((\text{average A} - \text{average B}) / \text{average A})$. The average error tolerance of the bulge depth measurement was maximum $\pm 8.3\%$. The error tolerance of the measurement was max 8%.

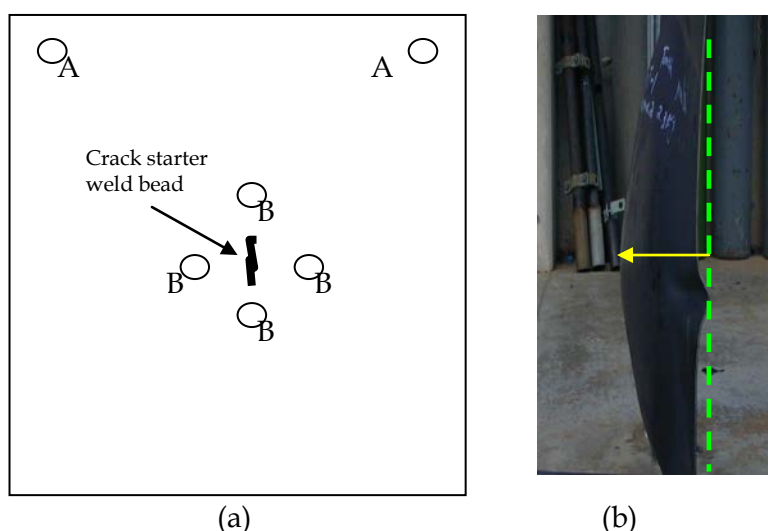


Figure 2: (a) Schematic diagram of the 6 point system of measurement for plate thinning percentage measurement system. The position of the crack starter weld bead is also shown; (b) schematic bulge depth measurement. The bulge depth measurement is measured along the yellow line from the green line to the point of maximum bulge height.

2.2 Test Parameters

Test parameters in this program of work are summarized below:

Cardboard insulation

In the recent tests, some of the target plates were wrapped with cardboard for insulation during transport from the temperature-conditioning chamber to the blast chamber. The testing was then undertaken with the cardboard in place. This differs from previous practice where plates were not covered during testing. In the current tests, the bulge depth and thinning of the test plates with and without cardboard wrapping (CBW) were measured to see if this parameter is significant in the material blast resistance.

Replacement of cardboard box with suspended charge

Figure 3a shows the test setup in which the die block is covered with a cardboard box enclosure (CBE) to maintain a 320 mm standoff from the bottom of explosive charge to the top of the target plate. In the tests reported here, an alternate setup was used in which the charge was suspended from the chamber ceiling as shown in Figure 3b.

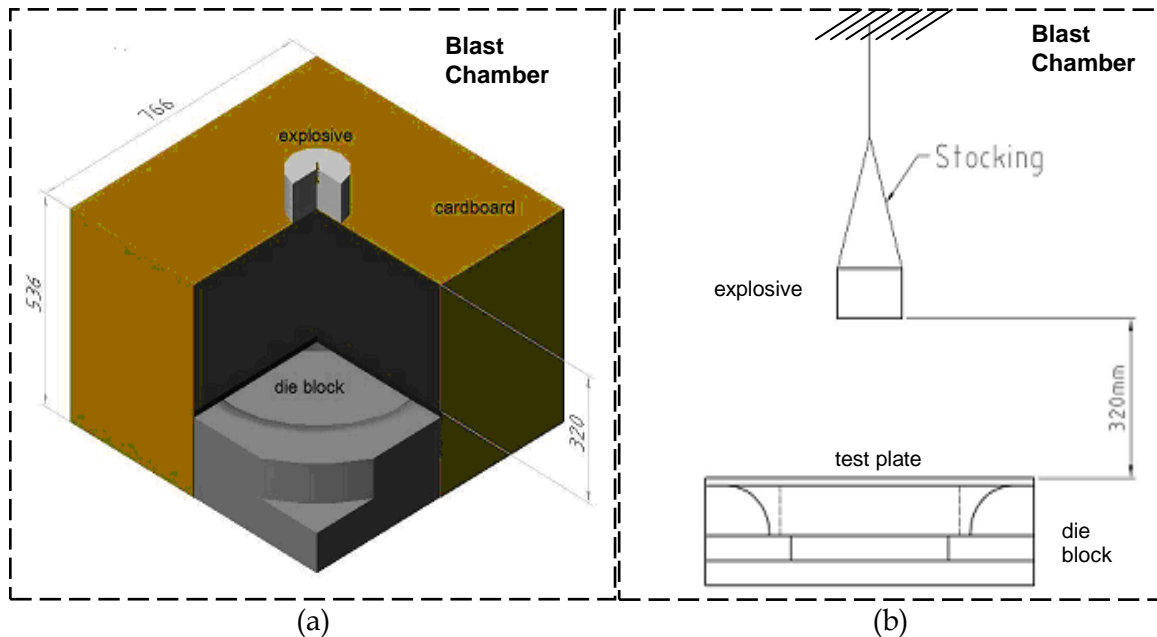


Figure 3: Standard test setup (a) a structural design with charge supported over the test plate by a cardboard box enclosure and (b) another means of supporting the charge above the plate by a suspended stocking which is held from the ceiling of the 3.5 m × 5 m × 3 m blast chamber by a string.

Crack starter

The crack starter is introduced in the form of a weld beads run on the bottom surface of the plate to be tested and it was oriented along the rolling direction of the plate to promote the initial cracking. All the plates were supported by cardboard wrapping and cardboard box enclosure. The plate temperature equilibrated at approximately -18 °C and this temperature condition was applied to all plates before testing. Only tests performed with 0.46 kg charge weight and Grade 350 mild steel were considered.

Temperature effects

In the current work, the purpose of temperature effects is to qualify the steel for performance under blast loading in terms of plate thickness reduction and bulge depth. However, in traditional explosion bulge testing, it is normal to test at -18 °C in order to determine low temperature ductility of the steel. The metallurgical and mechanical properties of the material may change from ductile to brittle (lower toughness) at low temperatures. A number of tests have been performed at ambient temperature in this investigation, in order to assess the temperature effect on bulge depth. All the plates tested to determine temperature effects were inside cardboard wrapping and cardboard box enclosure.

3. Results and Discussion

This section reports on the experimental results and provides analyses of the EBT conducted on 350 grade mild steel plate material as a function of the four test parameters described in Section 2, as well as detailing the effects of these parameters on bulge depth.

3.1 Crack Starter Effects

Table 1 shows a section of the test data relevant to investigating the effect of the crack starter weld beads.

Table 1: The test data used to evaluate the effect of a crack starter weld beads.

ID	Thickness (mm)	BD (mm)	Thinning (%)	Temp (°C)	Crack Starter	CBW	CBE
A1	3.03	123	6.85	-18	Yes	yes	yes
A2	3.26	120	9.7	-18	No	yes	yes
A3	4.16	75	1.25	-17.5	Yes	yes	yes
A4	4.88	58	2.85	-18	No	yes	yes
A5	5.27	55.5	4.17	-18	Yes	yes	yes
A6	6.53	43	3.99	-18	No	yes	yes
A7	8.01	40	1.83	-18	No	yes	yes

The effect of crack starter weld beads on plate bulge depth for 350 grade mild steel is plotted in Figure 4. The blue and pink marks indicate the experiments with and without crack starter weld beads, respectively. As observed in Figure 4, there does not appear to be any significant difference between bulge depths with and without crack starter weld beads.

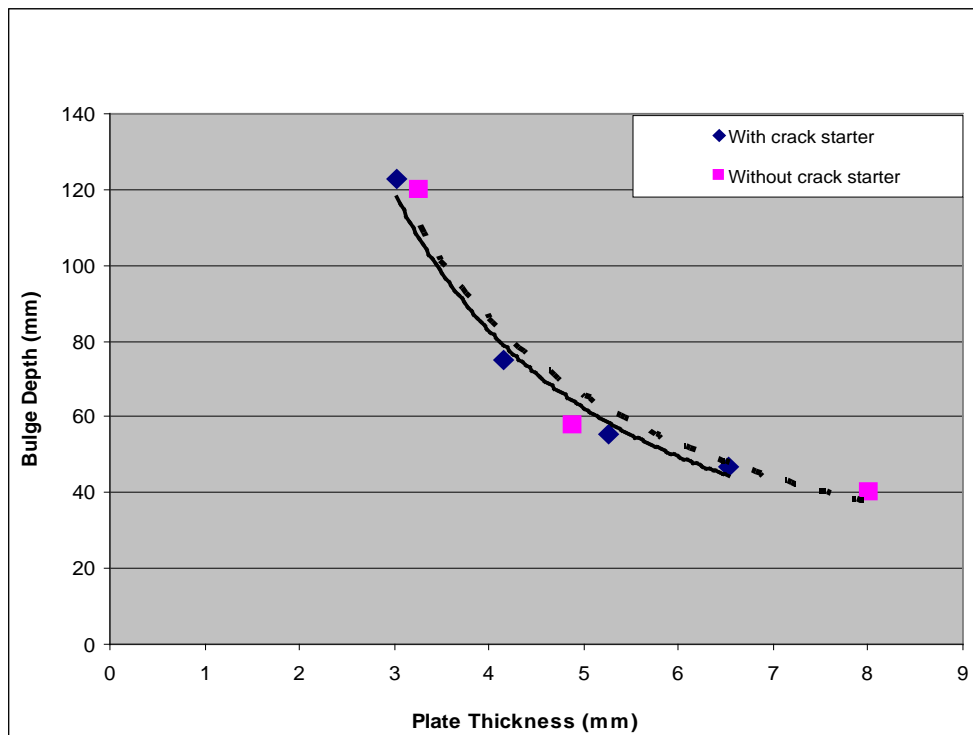


Figure 4: Bulge depth with and without crack starter weld beads for Grade 350 mild steel with 0.46 kg cylindrical charge weight and 100 mm cylinder charge diameter at AMT.

3.2 Temperature Effects

Table 2 shows the effect of plate temperature on bulge depth. Furthermore, Figure 5 shows the results of tests with bulge depth against plate thickness at two different charge diameters and two different temperatures. The dark blue and pink markers indicate the bulge depths at ambient temperature and at -18°C , respectively, with 160 mm cylindrical charge diameter (CCD). The yellow and light blue markers are at ambient temperature and -18°C , respectively, with 100 mm CCD. As shown in Figure 5, temperature has no significant influence on bulge depth. However, charge diameter can have a significant effect with larger diameter charges producing a significantly greater bulge depth. This is the subject of a separate report.

Therefore, it has been shown in this study that temperature effects on bulge depth for this material are negligible and thus it could be considered that for future EBT, ambient temperature for bulge depth measurement may be used. However, it will remain necessary to conduct explosion bulge testing at -18°C for new candidate armour steels in order to ensure the steel has adequate toughness at service temperatures [19].

Table 2: The test data used to evaluate the temperature effects. All the blast tests were performed with CBE.

ID	Thickness (mm)	BD (mm)	Thinning (%)	Charge Diameter (mm)	Temp (°C)	CBW
B1	3.11	164	9.97	160	16	yes
B2	3.26	120	9.70	100	-18	yes
B3	4.05	101.6	6.8	160	-18	yes
B4	4.4	79	0.46	100	18	yes
B5	4.88	58	2.85	100	-18	yes
B6	5.06	94	4.2	160	16	yes
B7	6.07	70	4.63	160	16.5	yes
B8	6.04	65	3.97	160	14.6	yes
B9	6.1	40	1.8	100	18	yes
B10	6.52	70.3	0.46	160	-18	yes
B11	6.81	65	3.32	160	17	yes
B12	8.05	46	0.46	160	-18	yes
B13	8.09	29	1.73	100	18	yes
B14	9.99	44	2.3	160	18	yes

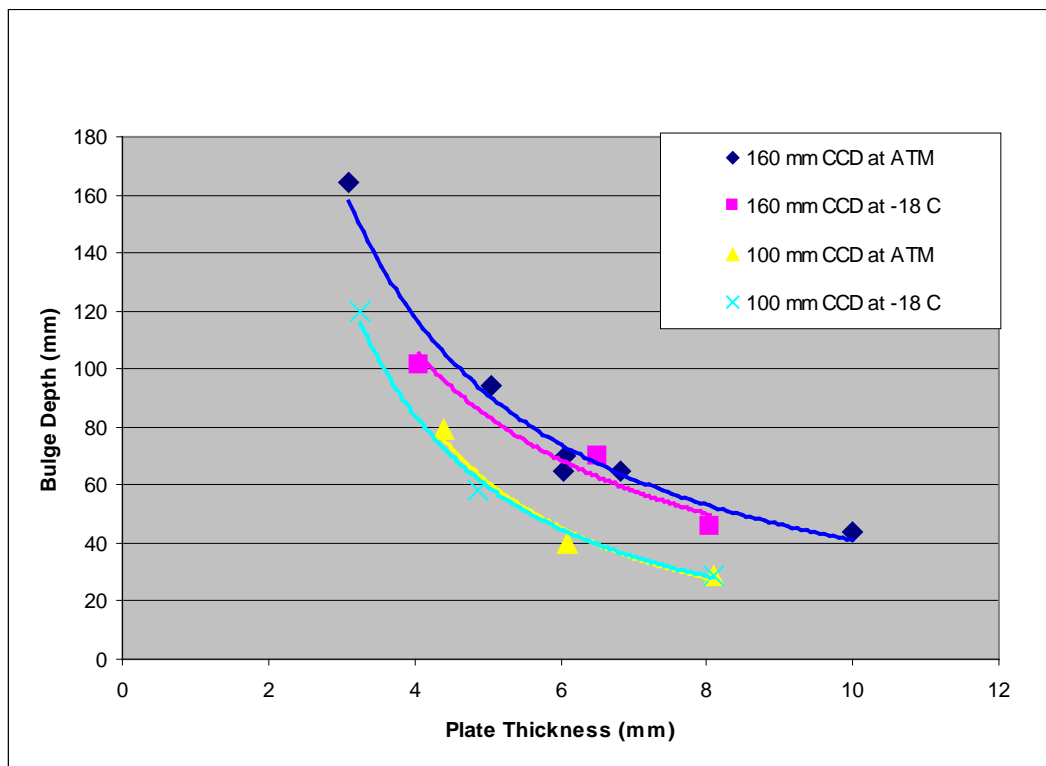


Figure 5: Bulge depth of Grade 350 mild steel at two different blast temperatures and charge diameters. Refer to Table 3.

3.3 Cardboard Wrapping (CBW) Effects

Table 3 and Figure 6 show the effects of cardboard wrapping on the bulge depth versus plate thickness relationship. The blue markers indicate the results with cardboard wrapping tested by 0.46 kg of charge weight using 100 mm charge cylinder diameter (CCD), while the pink markers show tests without wrapping. It is clear that the trend lines produced for EBT of 350 grade mild steel show no significant difference in bulge depth with and without CB wrapping as an insulator.

Table 3: Test data used to evaluate the cardboard wrapping effect.

ID	Thickness (mm)	BD (mm)	Thinning (%)	CBW
C1	2.99	117	12.7	no
C2	3.03	123	6.85	yes
C3	4.16	75	1.25	yes
C4	5.27	55.5	4.17	yes
C5	6.03	40.8	2.5	no
C6	8.06	30.5	2.13	no

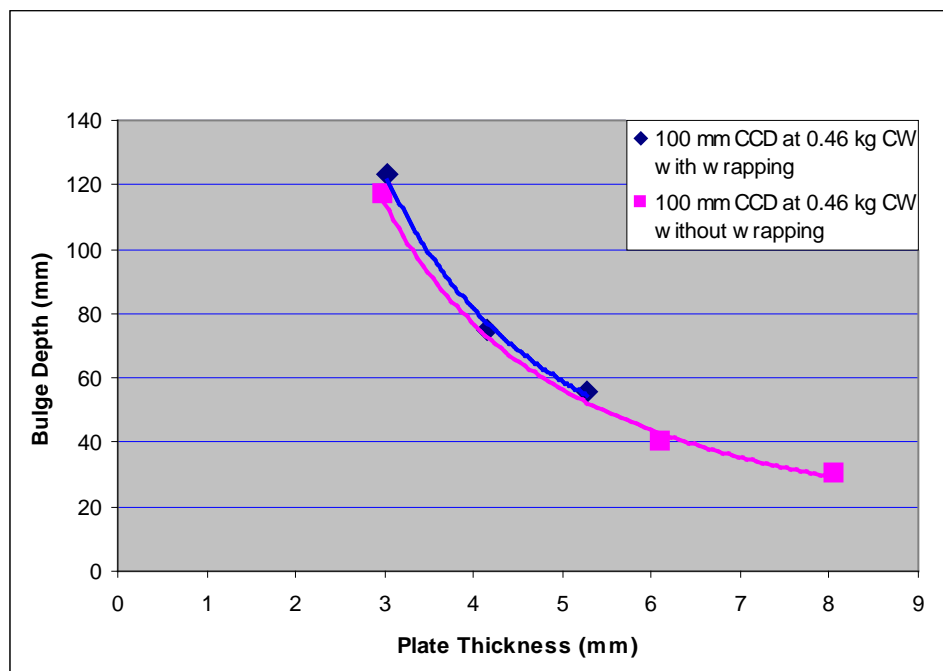


Figure 6: Bulge depth of Grade 350 mild steel with and without cardboard wrapping. Refer Table 3.

3.4 Effects of Charge Support Methods

Table 4 shows the test results of the effects of using a cardboard box enclosure versus a suspended charge to maintain charge height versus a suspended. Figure 7 shows the effect of charge support technique (CB box or suspended stocking) on the bulge depth vs. plate thickness relationship. Results show a measurable difference for the 160 mm diameter charge with plates tested using suspended charge showing increased deformation. For this reason, it is recommended that the results for the two conditions should not be compared directly. Results for the 100 mm diameter charge were similar irrespective of the mode of charge support. Refer to [20] about the effects of charge diameter differences.

Table 4 Test data used to evaluate CBE effects. 'No' defines the mode of charge suspension

ID	Thickness (mm)	BD (mm)	Thinning (%)	Charge Diameter (mm)	CBE
D1	2.99	117	12.7	100	no
D2	3.03	123	6.85	100	yes
D3	3.11	164	9.97	160	yes
D4	4.13	138	1.32	160	no
D5	4.16	75	1.25	100	yes
D6	5.27	55.5	4.17	100	yes
D7	5.06	94	4.2	160	yes
D8	6.04	65	3.97	160	yes
D9	6.1	40	1.8	100	no
D10	6.5	76	5.34	160	no
D11	6.81	65	3.32	160	yes
D12	8.05	49	1.01	160	yes
D13	8.09	29	1.73	100	no
D14	9.89	52	2.11	160	no

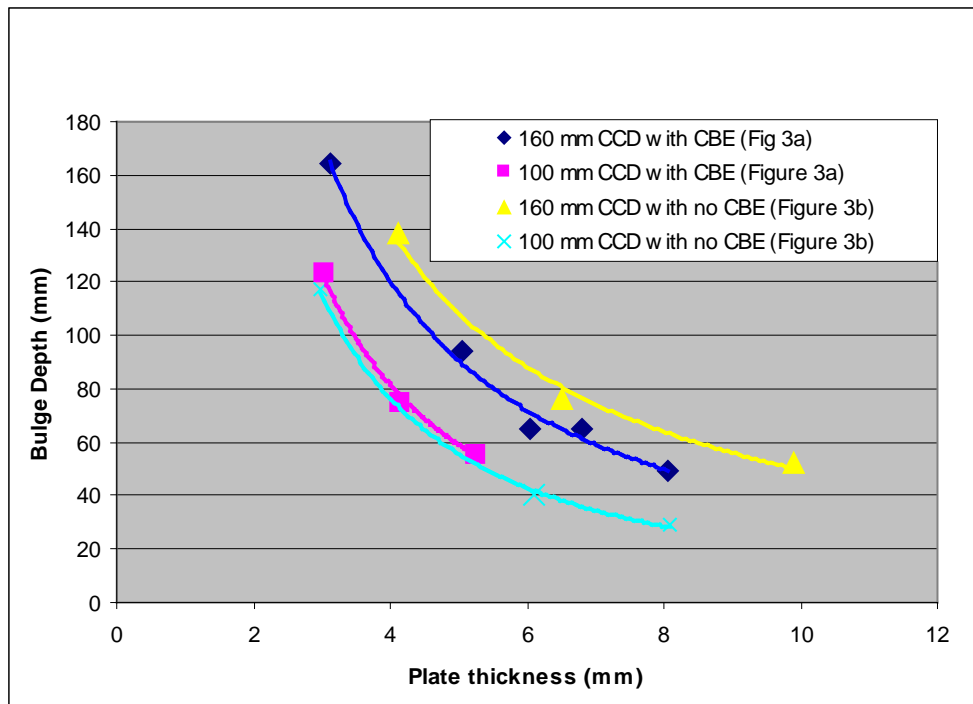


Figure 7: Effects of CCD and mode of charge suspension (Figure 3a and Figure 3b) on the bulge depth. Refer Table 4.

4. Conclusions

The four test parameters which may affect bulge depth as a result of EBT were systematically investigated in this study. These were crack starter weld beads, temperature, cardboard box enclosure to support charge and cardboard wrapping to maintain the required plate temperature. From this investigation, it was found that only the use of a cardboard box enclosure to support the charge affected bulge depth in the grade 350 grade steel. The other parameters assessed showed a negligible effect on bulge depth. However, it must be noted that these results can only be applied to 350 grade steel with plate thickness ranging from 2 to 10 mm.

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